Determining the CP parity of Higgs bosons at the LHC in their τ decay channels

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Abstract

If neutral Higgs bosons will be discovered at the CERN Large Hadron Collider (LHC) then an important subsequent issue will be the investigation of their *CP* nature. Higgs boson decays into τ lepton pairs are particularly suited in this respect. Analyzing the three charged pion decay modes of the τ leptons and taking expected measurement uncertainties at the LHC into account, we show that the *CP* properties of a Higgs boson can be pinned down with appropriately chosen observables, provided that sufficiently large event numbers will eventually be available.

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Introduction: The major physics goal of the upcoming experiments at the CERN Large Hadron Collider (LHC) is the exploration of the hitherto unknown mechanism of electroweak gauge symmetry breaking which, in the context of the standard model of particle physics (SM) and many of its extensions, is tantamount to searching for Higgs bosons, spin-zero and electrically neutral resonances with masses of (a few) hundred GeV (see, e.g., [1, 2] for reviews). If (one or several types of) Higgs bosons are found then the next issue will be the determination of their properties – in particular their parity (P) and charge conjugation times parity (CP) quantum numbers, respectively, which yield important information about the dynamics of these particles. While the SM Higgs boson is parity-even, SM extensions also predict parity-odd state(s) or, if the Higgs boson dynamics violates CP, states of un-defined CP parity with Yukawa couplings both to scalar and pseudoscalar quark and lepton currents. Higgs sector CP violation is a fascinating possibility, especially in view of its po-tentially enormous impact on an important issue of the physics of the early universe, namely baryogenesis [3]. These new interactions can be searched for at the upcoming generation of colliders in several ways (see [2] for a collection of recent results). The decays of Higgs bosons to $\tau^-\tau^+$ leptons and/or – if the Higgs bosons are heavy enough – to $t\bar{t}$ quarks are par-ticularly suited in this respect [4–10]. In this letter we show that, at the LHC, the CP nature of a neutral Higgs boson can be pinned down with appropriately chosen observables in its $\tau^-\tau^+$ decay channel where the τ decay into three charged pions, provided that sufficiently large event numbers will eventually be available.

The analysis of this letter applies to any neutral Higgs boson h_j with flavor-diagonal cou-plings to quarks and leptons f (with mass m_f)

$$\mathcal{L}_Y = -(\sqrt{2}G_F)^{1/2}\sum_{j,f}m_f(a_{jf}\bar{f}f+b_{jf}\bar{f}i\gamma_5 f)h_j\,, \tag{1}$$

where G_F is the Fermi constant and a_{jf} and b_{jf} are the reduced scalar and pseudoscalar Yukawa couplings respectively, which depend on the parameters of the (effective) Higgs po-tential of the respective model. In the SM, $a_f = 1$ and $b_f = 0$. As far as SM extensions are concerned we consider here, for definiteness, models with two Higgs doublets, such as the non-supersymmetric type II models and the minimal supersymmetric SM extension (MSSM) (see, e.g., [1, 2]). These models contain three physical neutral Higgs fields h_j in the mass basis. If Higgs sector CP violation (CPV) is negligibly small then the fields h_j describe two scalar states h, H ($b_f = 0$) and a pseudoscalar A ($a_f = 0$). In the case of Higgs sector CPV, the h_j have non-zero couplings[1] a_{jf} and b_{jf} to quarks and leptons which lead to CP-violating effects in $h_j \to f\bar{f}$ already at the Born level [4]. This is in contrast to the couplings to W^+W^- and to ZZ boson pairs of such a state of undefined CP parity. At the

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[1]They can be parameterized in terms of the ratio of the Higgs field vacuum expectation values $\tan\beta = v_2/v_1$ and a 3×3 orthogonal matrix that describes the mixing of the neutral spin-zero CP eigenstates [11].

Born level, only the CP $= +1$ component of h_j couples to W^+W^- and to ZZ. The coupling of the pseudoscalar component of h_j – if there is any – to W^+W^- and to ZZ is likely to be very small as it must be induced by quantum fluctuations. Thus, the observation of Higgs boson production in weak vector boson fusion $W^+W^-, ZZ \rightarrow h_j$ or of the decay channels $h_j \rightarrow W^+W^-, ZZ$ would tell us that h_j has a significant scalar component. However, the question would remain whether or not h_j is a pure $J^{PC} = 0^{++}$ state or if it has a significant pseudoscalar component, too[2] . This can be answered by investigating the τ decay channel of this particle.

τ spin observables: In the following, we choose the generic notation ϕ for any of the neutral Higgs bosons h_j discussed above. The observables discussed here for determining the CP quantum number of ϕ in its decay channel $\phi \rightarrow \tau^-\tau^+$ may be applied to any Higgs production process. At the LHC, this includes the gluon and gauge boson fusion processes $gg \rightarrow \phi$ and $q_iq_j \rightarrow \phi q'_iq'_j$, respectively, and the associated production $t\bar{t}\phi$ or $b\bar{b}\phi$ of a light Higgs boson. We consider the following semi-inclusive reactions

$$i \rightarrow \phi + X \rightarrow \tau^-(\mathbf{k}_\tau, \alpha) + \tau^+(\mathbf{k}_{\bar{\tau}}, \beta) + X, \tag{2}$$

where i is some partonic initial state, $\mathbf{k}_\tau$ and $\mathbf{k}_{\bar{\tau}} = -\mathbf{k}_\tau$ are the 3-momenta of τ^- and τ^+ in the $\tau\bar{\tau}$ zero-momentum frame (ZMF), and α, β are spin labels. Here we make use of the fact that at colliders polarization and spin correlation effects are both measurable and reliably predictable for tau leptons.

Let us assume that experiments at the LHC will discover a neutral boson resonance in a reaction of the type (2) and a sufficiently large sample will eventually be accumulated. The spin of ϕ may be inferred from the polar angle distribution of the tau leptons. Suppose the outcome of this analysis is that ϕ is a spin-zero (Higgs) particle. One would next like to determine its Yukawa coupling(s), and specifically like to know whether ϕ is a scalar, a pseudoscalar, or a state with undefined CP parity. This can be investigated by using the following CP-even and -odd observables involving the spins of $\tau, \bar{\tau}$, and we emphasize that all of them should be used. The correlation resulting from projecting the spin of τ onto the spin of $\bar{\tau}$,

$$S = \mathbf{s}_\tau \cdot \mathbf{s}_{\bar{\tau}}, \tag{3}$$

is the best choice for discriminating between a $CP = \pm 1$ state [5]. Here $\mathbf{s}_\tau, \mathbf{s}_{\bar{\tau}}$ denote the spin operators of τ^- and τ^+, respectively. This can be understood as follows. If ϕ is a scalar ($J^{PC} = 0^{++}$) then $\tau\bar{\tau}$ is in a $^3P_0$ state, and $\langle \mathbf{s}_\tau \cdot \mathbf{s}_{\bar{\tau}} \rangle = 1/4$. If ϕ is a pseudoscalar ($J^{PC} = 0^{-+}$)

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[2] Nevertheless, it can be checked with appropriate correlations whether or not there is a sizeable effective pseudoscalar coupling to weak vector bosons [12].

then $\tau\bar{\tau}$ is in a $^1S_0$ state and $\langle \mathbf{s}_\tau \cdot \mathbf{s}_{\bar{\tau}} \rangle = -3/4$, which is strikingly different from the scalar case. For general couplings (1) one gets $\langle S \rangle = (a_\tau^2 - 3b_\tau^2)/(4a_\tau^2 + 4b_\tau^2)$, using that $m_\phi \gg m_\tau$ [5]. If $\gamma_{CP}^\tau \equiv -a_\tau b_\tau \neq 0$, the Yukawa interactions of ϕ to τ leptons are not CP-invariant. This leads to CP-violating effects in the reactions (2). For an unpolarized initial state i, a general kinematic analysis of (2) yields the following result [4, 6]. If C-violating interactions do not matter in (2) then $\mathcal{L}_Y$ (which is C-invariant, but P- and CP-violating) induces two types of CPV effects: a CP-odd $\tau^-\tau^+$ spin-spin correlation and a CP-odd τ polarization asymmetry which correspond to the observables

$$S_{CP} = \hat{\mathbf{k}}_\tau \cdot (\mathbf{s}_\tau \times \mathbf{s}_{\bar{\tau}}), \quad S'_{CP} = \hat{\mathbf{k}}_\tau \cdot (\mathbf{s}_\tau - \mathbf{s}_{\bar{\tau}}). \tag{4}$$

Here, $\hat{\mathbf{k}}_\tau = \mathbf{k}_\tau/|\mathbf{k}_\tau|$ in the $\tau\bar{\tau}$ ZMF[3]. The CP-odd and T-odd[4] variable S_{CP} measures a correlation of the spins of the τ^- and τ^+ transverse to their directions of flight. A non-zero expectation value is generated already at tree level, $\langle S_{CP} \rangle = -a_\tau b_\tau/(a_\tau^2 + b_\tau^2)$ [4], which can be as large as 0.5 in magnitude. The variable S'_{CP} measures an asymmetry in the longitudinal polarization of the τ^- and τ^+. As it is CP-odd but T-even, a non-zero $\langle S'_{CP} \rangle$ requires both $\gamma_{CP}^\tau \neq 0$ and a non-zero absorptive part of the respective scattering amplitude.

(Multi) pion final states: The polarization and spin-correlation effects induced in the $\tau^-\tau^+$ sample from Higgs boson decay lead in turn, through the parity-violating weak decays of the τ leptons, to specific angular distributions and correlations in the respective final state which can be measured with appropriately constructed observables (see below). In order to obtain sufficient sensitivity to the CP properties of the Higgs boson resonance, one should consider τ decay channels that have both good to maximal τ-spin analyzing power and allow for the reconstruction of the τ decay vertex, i.e., the τ rest frame, which is essential for an efficient helicity analysis.

We recall the τ-spin analyzing power of the final state a in the decay $\tau^- \to a + \nu_\tau$, that is, the coefficient c_a in the distribution $\Gamma_a^{-1} d\Gamma_a/d\cos\theta_a = (1 + c_a \cos\theta_a)/2$, where θ_a is the angle between the τ^- spin vector and the direction of a in the τ^- rest frame (c.f., e.g., [13]). CP invariance which is, as known from experiments, a good symmetry in τ decays at the level of precision required here implies that the τ-spin analyzing power of $\bar{a}$ in $\tau^+ \to \bar{a} + \bar{\nu}_\tau$ is $c_{\bar{a}} = -c_a$.

The π^- channel is known to have maximal spin-analyzing power, $c_{\pi^-} = 1$. In the case of, e.g., multi-pion decays of the τ, this optimum analyzing power can also be achieved if all the pions are observed and the dependence of the hadronic current on the pion momenta is

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[3]Two more terms can appear in the squared matrix element of (2). They are obtained by replacing $\hat{\mathbf{k}}_\tau \to \hat{\mathbf{p}}$ in (4), where $\hat{\mathbf{p}}$ is the direction of one of the colliding beams in i. However, for resonant ϕ production only the observables (4) are of interest.

[4]Here T-even/odd refers to a naive T transformation, i.e., reversal of momenta and spins only.

known [14–16]. The latter is obtained using empirically tested matrix elements and fits to measured distributions.

In the following section we consider the decay $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ and the corresponding decay of τ^+. As this decay proceeds to a large extent via the a_1 resonance, we use $\tau^\mp \to a_1^\mp$ for the description of the three-pion final state. The measured pion momenta in the laboratory frame allow, using known kinematic distributions [13–15], the separation of the longitudinal (a_{1L}) and transverse (a_{1T}) helicity states of the a_1. This leads to an optimal spin analyzing power, $c = \pm 1$ for a_{1L} and a_{1T}, respectively. Moreover, the measured pion momenta yield the τ decay vertex and, in turn, the τ rest frame (see below).

We thus investigate reactions of the following type:

$$p\,p \to \phi + X \to \tau^-(\mathbf{k}_\tau, \alpha) + \tau^+(\mathbf{k}_{\bar\tau}, \beta) + X \to a(\mathbf{q}_1) + \bar{b}(\mathbf{q}_2) + X, \qquad (5)$$

where a and $\bar{b}$ denote here the a_1^- and a_1^+ resonances, respectively. Without loss of generality, we consider the a_{1L}^- and a_{1L}^+ states and comment on how the resulting distributions change when one or two a_{1T} are involved. The momenta of τ^- and τ^+ in (5) are defined as above in the $\tau\bar\tau$ ZMF, while the momenta $\mathbf{q}_1$ and $\mathbf{q}_2$ refer to the τ^- and τ^+ rest frames, respectively. Let's now come to the equivalents of the S_i at the level of the final states $a, \bar{b}$. The spin correlation $\langle S \rangle$ leads to a non-isotropic distribution in $\cos\varphi$, where $\varphi = \angle(\mathbf{q}_1, \mathbf{q}_2)$. If no phase space cuts are applied – modulo cuts on the invariant mass $M_{\tau\bar\tau}$ of the τ pair – this opening angle distribution is of the form [5]:

$$\frac{1}{\sigma_{a\bar{b}}} \frac{d\sigma_{a\bar{b}}}{d\cos\varphi} = \frac{1}{2}\left(1 - D_{a\bar{b}} \cos\varphi\right), \quad D_{a\bar{b}} = \frac{4}{3} c_a c_b \langle \mathbf{s}_\tau \cdot \mathbf{s}_{\bar\tau} \rangle. \qquad (6)$$

The coefficients $D_{a_{1L}^- a_{1L}^+} = D_{a_{1T}^- a_{1T}^+}$ are 0.33 and -1 for the channels $\phi(0^{++}) \to \tau\tau \to a_{1i}a_{1j}$ and $\phi(0^{-+}) \to \tau\tau \to a_{1i}a_{1j}$, respectively, if $ij = LL, TT$, while they change sign if $ij = LT, TL$. Thus, for $ij = LL, TT$ the a_1 momenta $\mathbf{q}_1, \mathbf{q}_2$ are predominantly parallel in the case of a pseudoscalar ϕ, while for a scalar ϕ they tend to be antiparallel.

The equivalents of the CP-odd spin observables S_{CP} and S'_{CP} at the level of the final states (5) are [5, 6]:

$$O_{CP} = (\hat{\mathbf{k}}_\tau - \hat{\mathbf{k}}_{\bar\tau}) \cdot (\hat{\mathbf{q}}_2 \times \hat{\mathbf{q}}_1)/2, \quad O'_{CP} = \hat{\mathbf{k}}_\tau \cdot \hat{\mathbf{q}}_1 - \hat{\mathbf{k}}_{\bar\tau} \cdot \hat{\mathbf{q}}_2. \qquad (7)$$

In general, if $b \neq a$ the averages of (7) should be taken for events (5) plus the charge conjugated events $\bar{a}b$. Asymmetries corresponding to (7) are:

$$A(O) = \frac{N_{a\bar{b}}(O > 0) - N_{a\bar{b}}(O < 0)}{N_{a\bar{b}}}, \qquad (8)$$

where $N_{a\bar{b}}$ is the number of events in the reaction (5). If no phase-space cuts, besides cuts on $M_{\tau\bar\tau}$, are imposed then [6]

$$\langle O_{CP} \rangle_{a\bar{b}} = -\frac{4}{9} c_a c_{\bar{b}} \langle S_{CP} \rangle, \quad \langle O'_{CP} \rangle_{a\bar{a}} = \frac{2}{3} c_a \langle S'_{CP} \rangle,$$

$$A(O_{CP}) = \frac{9\pi}{16}\langle O_{CP}\rangle_{a\bar{b}}, \quad A(O'_{CP}) = \langle O'_{CP}\rangle_{a\bar{a}}. \tag{9}$$

Here the relations involving O'_{CP} are given for simplicity for the diagonal channels $a\bar{a}$ only. The observable O_{CP} measures the distribution of the signed normal vector of the plane spanned by $\mathbf{q_1}, \mathbf{q_2}$ with respect to the τ^- direction of flight. If $\gamma_{CP}^\tau \neq 0$ then this distribution is asymmetric. If ϕ were an ideal mixture of a CP-even and -odd state, $|a_\tau| = |b_\tau|$, the asymmetry corresponding to O_{CP} would take the value $|A(O_{CP})| = 0.4$ in the $a_{1i}a_{1j}$ channels $(i,j = L,T)$. As already mentioned, $\langle O'_{CP}\rangle \neq 0$ also requires, besides $\gamma_{CP}^\tau \neq 0$, an absorptive part in the scattering amplitude $i \to \phi \to \tau^-\tau^+$, which is small in our analysis below. Therefore, we do not consider this observable any further.

Results: For non-standard Higgs bosons ϕ and large $\tan\beta$, the associated production with bottom quarks, $gg \to b\bar{b}\phi$, is considered to be the most promising mode in the $\phi \to \tau\bar{\tau}$ decay channel at the LHC [17, 18]. The results shown below are not only applicable to this production process, but also to gluon-gluon fusion, $gg \to \phi$, and vector boson fusion. The reason is that our normalized distributions do not depend on the ϕ momentum if no detector cuts are applied. Furthermore we show for $\phi \to \tau\bar{\tau} \to a_1\bar{a}_1$ that detector cuts have only a very small effect on these distributions for Higgs masses larger than 200 GeV. Thus, our results will not change significantly for the different Higgs production modes or if initial-state higher-order QCD corrections are taken into account. We have, therefore, computed in this analysis all distributions for a generic $2 \to 1$ Higgs boson production process at leading order.

As emphasized above, the determination of the distributions of $\cos\varphi$ and of the observable O_{CP} requires the reconstruction of the $\tau^\mp$ rest frames. For the decay channels (5), the $a_1^\mp$ momenta in the laboratory frame and the $\tau^\mp$ decay vertices can be obtained from the visible tracks of the three charged pions. The $\tau^\mp$ production, i.e., the Higgs production vertex, can be reconstructed from the visible tracks of the charged particles/jets produced in association with the ϕ [19]. Using that, for each τ, $\tilde{k}_\tau^\mu = \tilde{q}_{a_1}^\mu + \tilde{q}_\nu^\mu$, $m_\tau^2 = \tilde{E}_\tau^2 - \tilde{\mathbf{k}}_\tau^2$, $\tilde{E}_\nu^2 = \tilde{\mathbf{q}}_\nu^2$ (the tilde refers to the laboratory frame), and $\tilde{\mathbf{k}}_\tau = \kappa\hat{\mathbf{x}}$, where $\hat{\mathbf{x}}$ is the unit vector along the line connecting the τ production and decay vertex, the factor κ is obtained by solving this system of equations. For each τ lepton, we obtain two solutions, and we select the solution for which the sum of the transverse $\tau^\mp$ momenta is closest to zero. With this solution for $\tilde{k}_\tau^{\mu\mp}$ the $\tau^\mp$ rest frames and the momentum directions $\hat{\mathbf{q}}_{1,2}$ can be reconstructed, which are required for the observables (6), (7), and (8).

Fig. 1a shows the $\cos\varphi$ distributions for the production of a scalar $\phi = H$ and a pseudoscalar $\phi = A$ in the decay channel (5), assuming a mass $m_{H,A} = 200$ GeV, both for no detector cuts and for applying the cuts $p_T \geq 40$ GeV and $\eta \geq 2.5$ (pseudorapidity) on the pions in the final state. In fact, the cut on η does not change the shape of the normalized distributions

shown in Fig. 1. The figure shows that the p_T cuts have only a very minor influence, too. The slopes are given to very good approximation by the numbers below in (6). This implies that the shape of these distributions will be quite stable with respect to inclusion of higher order QCD corrections. The influence of the cuts on the shape of the distributions decreases for larger ϕ masses. Only for light Higgs masses $m_\phi \gtrsim 120$ GeV does the chosen minimum p_T cut of 40 GeV have a more significant effect.
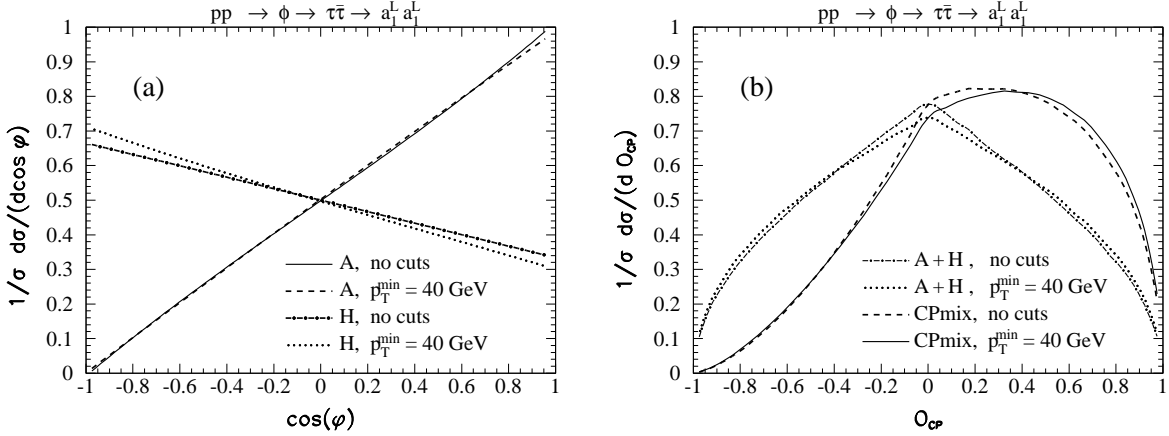

Figure 1: Distributions of $\cos\varphi$ (a) and O_{CP} (b) for $m_\phi = 200$ GeV and a_1 polarizations LL or TT.

Let us now discuss the following two situations: i) Suppose both a scalar and a pseudoscalar Higgs boson with (nearly) degenerate masses, for instance $m_{H,A} \sim 200$ GeV, exist and are produced in the reaction (5), $i \to H, A$. Such degenerate resonances cannot be resolved, e.g., in the $M_{\tau\bar{\tau}}$ spectrum. The resulting $\cos\varphi$ distribution will have a shape somewhere between the scalar and pseudoscalar extremes shown in Fig. 1a, depending on the relative reaction rates. ii) Suppose, on the other hand, that a Higgs boson ϕ with $m_\phi \sim 200$ GeV exists[5] which has both scalar and pseudoscalar couplings to fermions, in particular to τ leptons. The slope of the resulting $\cos\varphi$ distribution will also differ from the two extremes shown in Fig. 1a. In other words, the measured distribution does not tell whether degenerate scalar and pseudoscalar resonances or a state of undefined CP parity were produced. This puzzle may be resolved using the observable O_{CP}. As case i) corresponds to a CP-invariant Higgs sector, the resulting distribution of O_{CP} must be symmetric (if the phase space cuts are CP-symmetric) and $\langle O_{CP} \rangle = 0$, while case ii) will produce an asymmetric distribution and a non-zero average. This is shown in Fig. 1b, where case ii) is illustrated with an "ideal mixture" (label *CPmix*), i.e., a ϕ boson with scalar and pseudoscalar couplings of equal magnitude – we put $a_\tau = -b_\tau$. Again, the applied cuts have only a minor influence on the distributions. As already mentioned above the distributions in Figs. 1a, b do not change if both intermediate

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[5]Of course, Higgs bosons of this type might also be degenerate; for simplicity we do not consider this possibility here.

a_1 are transversely polarized, while they are reflected with respect to the vertical line passing the abscissa value zero in the case of mixed polarizations.

An important question is how robust is the discriminating power of these distributions with respect to experimental errors. In order to study this issue, using Monte Carlo methods, we have accounted for the expected measurement uncertainties by "smearing" the relevant quantities with a Gaussian according to $\exp(-(x/\sigma)^2/2)$, where x denotes the generated quantity (position in x space, momentum component, energy) and σ its expected standard deviation (s.d.). We use here $\sigma_z^P = 15\,\mu m$, $\sigma_T^S = 15\,\mu m$, $\sigma_L^S = 500\,\mu m$, $\sigma_\theta^{a_1} = 0.8\,\text{mrad}$, $\delta E/E = 2\%$, where σ_z^P denotes the s.d. of the position of the τ production vertex along the beam axis, while σ_L^S and σ_T^S are the s.d. of the positions of the respective τ decay vertex along the τ-jet axis (i.e., the direction of a_1) and in the plane transverse to this axis. Furthermore, the uncertainty in determining the direction of a_1 is parameterized by an angle θ with s.d. $\sigma_\theta^{a_1}$, and $\delta E/E$ denotes the relative error of determining the energy of a_1. These values appear to be realistic for the LHC experiments [19, 20]. For this simulation we use, in the case of $m_\phi = 200$ GeV, a constant τ flight length of 4.5 mm.

The effect of these uncertainties on the distributions of $\cos\varphi$ and O_{CP} is shown in Figs. 2a, b, using again Higgs boson masses $m_\phi = 200$ GeV. For the above set of uncertainties, scalar and pseudoscalar states are still clearly distinguishable (Fig. 2a), and likewise, *CP*-conserving and *CP*-violating states (Fig. 2b). We have made a systematic study by varying i) the masses
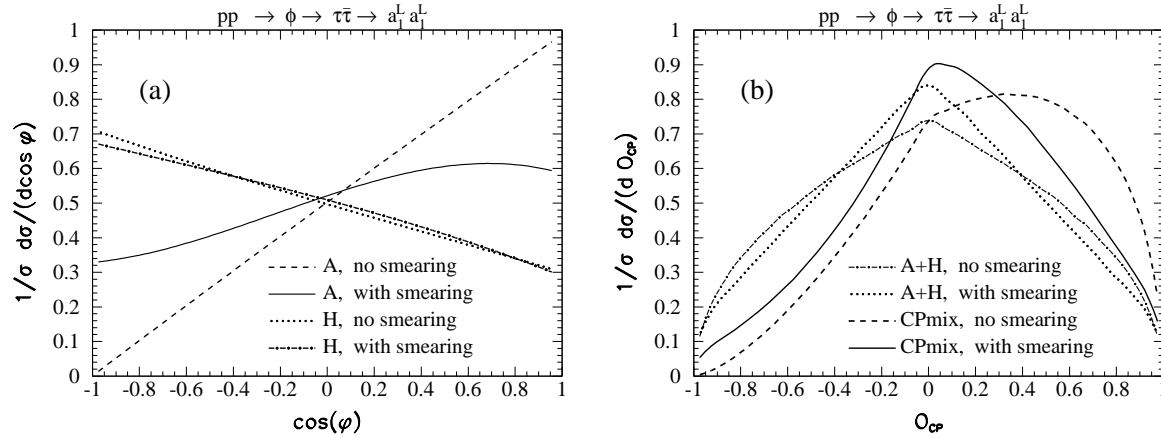

Figure 2: Distributions of $\cos\varphi$ (a) and O_{CP} (b) taking into account measurement uncertainties and cuts.

m_ϕ of the various types of Higgs bosons between 120 GeV and 500 GeV and ii) the expected measurement errors. Varying m_ϕ we found that the discriminating power of these distributions does not decrease for heavy Higgs bosons. This can be understood as follows. When m_ϕ is increased the angle between the τ and a_1 directions in the laboratory frame decreases, which implies that the dependence on the smearing parameters of the distributions is becoming stronger. On the other hand, the fact that the average flight length of the τ leptons

is becoming larger reduces the sensitivity to the smearing parameters, leaving the overall dependence of the distributions on the above set of uncertainties rather stable. Concerning measurement errors we found that it is important to have under control the transverse uncertainty σ_T^S in the reconstruction of the τ decay vertices and also the uncertainties σ_z^P and $\sigma_\theta^{a_1}$ of the position of the τ production vertex and of θ. In order to make use of the discriminating power of the above observables, one should achieve $\sigma_T^S < 18\,\mu m$, $\sigma_z^P < 30\,\mu m$, and $\sigma_\theta^{a_1} < 1\,\text{mrad}$ in future experiments. Least critical are the resolution of the longitudinal τ-jet axes (σ_L^S) and the energy uncertainty of the a_1 meson. Details of our results will be given elsewhere [21].

Finally, we estimate how many events (5) are needed in order to discriminate between i) a scalar and pseudoscalar Higgs boson and/or ii) between *CP*-conserving and *CP*-violating states, assuming $m_\phi = 200$ GeV. As to i), we define an asymmetry $A_\varphi = [N(\cos\varphi > 0) - N(\cos\varphi < 0)]/[N_> + N_<]$. From Fig. 2a we obtain from the smeared distributions $A_\varphi^H = -0.19$ and $A_\varphi^A = 0.17$. Thus, for distinguishing H from A with 3 s.d. significance requires 69 events (5). Concerning ii), the result of Fig. 2b implies that for an ideal *CP* mixture the CP asymmetry (9) takes the value $A(O_{CP}) = 0.23$ while it is zero for pure H, A, and degenerate H and A intermediate states. Thus, 170 events (5) will be needed to establish this CPV effect at the 3 s.d. level. This may be feasible, depending on the masses and couplings of ϕ, after several years of high luminosity runs at the LHC [17, 18]. The τ data sample will be increased by an order of magnitude if the above observables can be applied also to one-prong hadronic τ decays. This is currently being investigated, employing appropriately constructed pseudo rest-frames [21].

Conclusions: The τ decay channel is clearly most suited to explore the *CP* nature of a light or heavy neutral Higgs boson ϕ. This is an important physics issue if Higgs bosons are discovered. We have discussed a set of observables that serve this purpose, and we have shown, for Higgs boson production at the LHC and its decay via τ leptons into a_1 mesons, that the above correlations and asymmetries provide powerful tools for discriminating between *CP*-even and -odd Higgs bosons and for searches for *CP* violation in the Higgs sector. The measurement of these observables is challenging, but our analysis indicates that it should be feasible in the long run, provided enough $\phi \to \tau\tau$ events will be recorded at the LHC.

References

[1] A. Djouadi, arXiv:hep-ph/0503172; arXiv:hep-ph/0503173.

[2] E. Accomando *et al.*, arXiv:hep-ph/0608079.

[3] A. G. Cohen, D. B. Kaplan and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. **43**, 27 (1993).

[4] W. Bernreuther and A. Brandenburg, Phys. Lett. B **314**, 104 (1993); Phys. Rev. D **49**, 4481 (1994).

[5] W. Bernreuther, A. Brandenburg and M. Flesch, Phys. Rev. D **56**, 90 (1997).

[6] W. Bernreuther, A. Brandenburg and M. Flesch, arXiv:hep-ph/9812387.

[7] J. R. Dell'Aquila and C. A. Nelson, Nucl. Phys. B **320**, 86 (1989).

[8] D. Chang, W. Y. Keung and I. Phillips, Phys. Rev. D **48**, 3225 (1993).

[9] M. Krämer, J. H. Kühn, M. L. Stong and P. M. Zerwas, Z. Phys. C **64**, 21 (1994).

[10] B. Grzadkowski and J. F. Gunion, Phys. Lett. B **350**, 218 (1995).

[11] W. Bernreuther, T. Schröder and T. N. Pham, Phys. Lett. B **279**, 389 (1992).

[12] J. R. Dell'Aquila and C. A. Nelson, Phys. Rev. D **33**, 80 (1986); T. Plehn, D. L. Rainwater and D. Zeppenfeld, Phys. Rev. Lett. **88**, 051801 (2002); C. P. Buszello *et al.*, Eur. Phys. J. C **32**, 209 (2004).

[13] A. Stahl, Springer Tracts Mod. Phys. **160**, 1 (2000).

[14] A. Rougé, Z. Phys. C **48**, 75 (1990).

[15] M. Davier, L. Duflot, F. Le Diberder and A. Rougé, Phys. Lett. B **306**, 411 (1993).

[16] J. H. Kühn, Phys. Rev. D **52**, 3128 (1995).

[17] "ATLAS detector and physics performance. Technical design report. Vol. 2,", report CERN-LHCC-99-15.

[18] G. L. Bayatian *et al.* [CMS Collaboration], J. Phys. G **34**, 995 (2007).

[19] S. Gennai *et al.* [CMS Collaboration], Eur. Phys. J. **C46, S01**, 1 (2006).

[20] F. Tarrade [ATLAS Collaboration], Nucl. Phys. Proc. Suppl. **169**, 357 (2007).

[21] S. Berge and W. Bernreuther, to be published.